Millisecond Pulsations from LMXBs: Future Observational Considerations

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Abstract.
RXTE has discovered a flurry of new accreting millisecond pulsars in the past two years, based on dedicated and all-sky monitoring. How could *RXTE* and an enhanced future timing mission capitalize on these successes? I argue that the major issues to tackle are binary orbit and spin evolution. There is enough potential uncertainty in the models that drive binary evolution that it is worth attempting to detect orbital period changes in millisecond pulars. With *RXTE* it is possible to measure the orbital phase to within a few to a few hundred microperiods, and that can be improved by a factor of ~ 3 with an enhanced timing mission with $\sim$10 times the collecting area. This in turn will make it possible to feasibly detect significant orbital period changes within a few years baseline. Neutron star spin torques due to accretion are also important, since they are presumably the mechanism by which low mass X-ray binaries are spun up to millisecond pulsars in the first place. The current ambiguous data on spin torques suggests that further, more ambitious studies are required. I also discuss several other issues, such as pulse phased spectroscopy, which may improve our knowledge of the neutron star equation of state. I conclude with a brief presentation of the "ideal" millisecond pulsar observatory.

1. INTRODUCTION

RXTE has made a significant contribution toward the discovery of millisecond accreting pulsars and the understanding of low mass X-ray binaries (LMXBs). After the initial discovery in 1998 of SAX J1808.4–3658 as a pulsar (Wijnands & van der Klis [29]; Chakrabarty & Morgan [4]), a flurry of new discoveries in 2002 and 2003 has resulted in an inventory of five systems (XTE J1751−305, Markwardt et al. [12]; XTE J0929−314, Galloway et al. [9]; XTE J1807−194, Markwardt et al. [13]; XTE J1814−338, Markwardt et al. [14]). In addition, the original system, J1808[1], has undergone two additional outbursts in 2000 and 2002, observed by *RXTE*. Detection from J1808 of X-ray bursts with oscillations at nearly the same frequency as the persistent pulsations have verified the interpretation of burst oscillations as arising from neutron star spin (Chakrabarty et al. [5]). Persistent kilohertz oscillations detected in the same outburst (Wijnands et al. [30]) have also confirmed that there is a relationship between neutron star spin and the approximate separation between kilohertz QPO peaks.

A legitimate question is, how can we capitalize on these successes and proceed from here? I will argue that the most fundamental areas that need our attention now relate to binary and spin evolution scenarios. Theoretical models provide predictions of the number of X-ray binaries in the galaxy, and coupled with observations, can constrain the mechanisms that produce them. These scenarios are being steadily improved with the input of new physics and higher fidelity models, but are still difficult to test because of the low number statistics in the galaxy, and the potential that many systems have a low active duty cycle and spend most of their time in quiescence (i.e. the "tip of the iceberg" effect). Ultimately, I believe that the detection of binary orbit and spin evolution in individual LMXB systems will provide the most constraints on current evolutionary models, but there are some other avenues to explore as well.

2. BINARY EVOLUTION THEORIES

The modeling of low mass binary evolution has been steadily improving, with the aid of more sophisticated models and computing machinery. Binary evolution scenarios can be generated by establishing a set of initial conditions and then allowing the system to evolve ac-

[1] For brevity hereafter, the pulsars will be referred to by their four digit right ascension only.

cording to known physics (e.g. Podsiadlowski et al. [19]; Nelson & Rappaport [17]). Physics terms include stellar structure, opacities, Roche lobe formation, mass transfer, angular momentum transfer, and potential mass loss from the system. Some terms are more physically motivated, while others are more phenomenological or ad hoc. For example, Podsiadlowski et al. [19] include detailed equations of state and molecular opacities. On the other hand, certain more or less arbitrary assumptions are made, such as the form of the "magnetic braking" law, and the fractional mass loss from the system (50%).

Appeals are often made to magnetic braking to extract angular momentum from the system. Under this model, if the companion star has an ionized wind and a strong enough magnetic field, then the wind will be forced to co-rotate with the star's field, and thus extract angular momentum from it. As the companion should be tidally locked to the orbital frequency, the magnetic braking effect should ultimately remove angular momentum from the entire system, including the orbit (Verbunt & Zwaan [28]; Rappaport Verbunt & Joss [21]). It is presumed that this effect dominates over gravitational radiation. The properties of magnetic braking are extrapolated from the spin histories of main sequence stars; it is unclear how well this extrapolation applies to the highly evolved and low mass companions of the millisecond accreting pulsars.

The evolutionary scenarios have been further enhanced, with the inclusion of initial distributions of binary stars, to generate complete population synthesis studies (Pfahl, Rappaport & Podsiadlowski [18]). Despite the assumptions mentioned, the models are very successful in reproducing the relative distributions of orbital periods of X-ray binaries in the period range $10^{-1.5}$–$10^{+1.5}$ days. The most significant problem with the models is a severe overproduction of low mass X-ray binaries, compared to the observed population, by a factor of 100–1000. There is clearly still work to do in refining the models, perhaps by including other effects such as irradiation and the bloating of the companion stars (e.g., Deloye & Bildsten [8]). Also, there is a long standing question, originally proposed by Kulkarni & Narayan [11], of whether there are enough X-ray binaries to account for the number of millisecond *radio* pulsars. Given these two factors, it seems quite possible that there is also a large population of quiescent low mass X-ray binary systems which ultimately become radio pulsars, and which have low outburst duty cycles and so are only rarely detectable.

Are we missing a lot of millisecond pulsar transients by not looking with dedicated observations? Examinations of the light curves of the known millisecond transients reveals that the peak fluxes for four of the five are between 35–65 mCrab (J0929, 35 mCrab; J1807, 40 mCrab; J1751, 55 mCrab; J1808, 65 mCrab) and one,

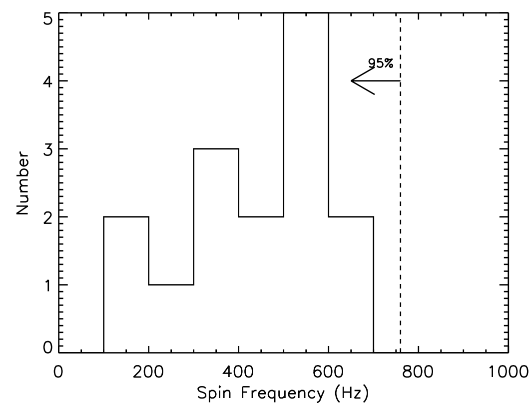

FIGURE 1. The distribution of low mass X-ray binary neutron star spin frequencies, based on the five known millisecond accreting pulsars and X-ray bursters with burst oscillations (Strohmayer & Bildsten [25]). Assuming a truncated flat distribution of neutron star spins, Chakrabarty et al. [5] derive the shown 95% confidence upper limit for the truncation point.

J1814, had a peak flux of $\sim$12 mCrab. Thus, four of the five systems would have been detectable with the present *RXTE* ASM in daily average analysis, if they had been far from the confusing galactic center (and J0929 was indeed detected in that manner). As the millisecond pulsar systems should trace their progenitor population, we expect most to be on or near the galactic bulge and plane. Of course, four of the known systems are within 10–20 degrees of the galactic center, where source confusion can reduce the sensitivity of the ASM, but any of those such systems would be detectable with the PCA bulge scan monitoring program, which has a detection threshold of (0.5–1 mCrab). In the course of 4–5 years of monitoring the galactic bulge, there have been several transients that have resembled millisecond pulsar system outbursts — similar peak fluxes and outburst durations — and yet no pulsations were detectable when follow-up PCA observations were performed.

I conclude that it is likely that we are not missing an overwhelming fraction of the millisecond pulsar transient outbursts, but it is possible that there are some undetected transient outbursts which are at or just below the detection threshold for the ASM, or concentrated near other confusing bright sources on the galactic ridge. An enhanced X-ray timing mission would need a significantly improved all-sky monitoring sensitivity ($\sim$few mCrab per day) in order to catch any of these potential transients.

3. SPIN DISTRIBUTION

Given the discovery that persistent millisecond pulsations are at the same frequency as nearly-coherent oscillations seen during thermonuclear X-ray bursts in J1808 (Chakrabarty et al. [5]; Strohmayer & Markwardt [24]), it is possible to take the joint set of accreting millisecond pulsars and burst oscillation sources and find their spin distributions (Figure 1). Chakrabarty et al. [5] conclude that, if the neutron star spins have a truncated flat distribution, then the 95% confidence spin frequency upper limit is ~ 750 Hz. It is unclear as to whether the assumed shape of the distribution is correct. Also, Chakrabarty et al.'s simple phenomenological model does not explain whether each system is at its equilibrium spin period, or is gradually evolving toward (say) higher frequencies. The upper cutoff is suggestive of true maximum (i.e. equilibrium) neutron spin rate of 750 Hz. Such a maximum might be imposed if gravitational radiation losses begin to dominate above a certain frequency (Bildsten [3]). However, for this mechanism to be effective, mass asymmetries must form in the neutron star, and persist, and it is not clear whether this can occur.

4. ORBITAL EVOLUTION

Given simple conservation equations, it is possible to derive constraints on the evolution of X-ray binaries. Binary orbital evolution is driven according to angular momentum conservation,

$$\frac{\dot{J}}{J} = \frac{\dot{m}_1}{m_1} + \frac{\dot{m}_1}{m_1} + \frac{\dot{a}}{2a} \tag{1}$$

where J is the system angular momentum, m_1 and m_2 are the primary and secondary masses (in solar units), and a is the binary separation. Using the constraint of Kepler's law, and assuming the secondary fills its Roche lobe, the evolution equation becomes

$$\frac{\dot{J}}{J} = -\frac{\dot{\nu}_b}{\nu_b}\frac{1}{g(n,q)} \tag{2}$$

where ν_b is the binary orbit frequency, and $g(n,q) = (3n-1)/(n+5/3-2q)$ is a function of order unity which depends on the equation of state of the secondary, $n = dR_2/dm_2 m_2/R_2$, and the mass ratio $q = m_2/m_1$. For small main sequence companion stars R_2 is approximately proportional to m_2, so $n_{\rm MS} \simeq 1$ and g is positive (~ 0.75). However, the companions of most of the accreting millisecond pulsars are likely to be quite degenerate, in which case $n \simeq -1/3$, and $g \sim -1.5$. Thus, we see that if angular momentum is removed from a binary system with a non-degenerate donor, the orbital frequency will increase (i.e., the orbit will tighten), while the opposite is true for a degenerate donor.

There are well-known mechanisms to remove angular momentum from the system. Gravitational radiation presumably always does so, and has a form

$$\left(\frac{\dot{J}}{J}\right)_{\rm GR} = -\frac{32G^3M_\odot^3}{5c^5}\frac{m_1 m_2(m_1+m_2)}{a^4}. \tag{3}$$

When expressed as a function of the orbital frequency, the orbital evolution equation becomes

$$\begin{aligned} \dot{\nu}_b &= +1.2\times10^{-17}\ \mathrm{Hz\ s^{-1}}\mu\ (m_1+m_2)^{2/3} \\ &\times \left(\frac{\nu_b}{10^{-3}\ \mathrm{Hz}}\right)^{11/3} g(n,q) \end{aligned} \tag{4}$$

where μ is the reduced mass, $m_1 m_2/(m_1+m_2)$. Given the strong dependence on orbital frequency, the largest orbital changes will obviously occur when the binary is tightest. For small companions, $\mu \sim m_2$, so the orbital change is also approximately proportional to the companion mass, and is least effective for the smallest companions.

For most binaries, including both LMXBs and CVs, it is well understood that gravitational radiation alone cannot remove enough angular momentum to drive the observed mass transfer rates, which has lead to the use of magnetic braking as a significant effect (Verbunt & Zwaan [28]). Observationally, main sequence stars are known to spin down as a function of age; when explained as a torque due to magnetic braking, the observations lead to the approximate relation

$$\dot{J}_{MB} = -1.9\times10^6\ \mathrm{g\ cm^{-2}s}\ m_2 R_\odot^4 \nu_b^3 \left(\frac{R_2}{R_\odot}\right)^\gamma. \tag{5}$$

The observations of main sequence stars leads to a value of $\gamma \sim 4$ (eg. Smith [23]), however, γ is often treated as a free parameter considering that the extrapolation of the observations may not apply exactly to very low mass, or highly evolved, stars. Recent evolutionary models tend to assume values of 4 (the original braking model; Podsiadlowski, Rappaport & Pfahl [19]) or 3 (Nelson & Rappaport [17]). Since the coronal field is commonly thought to originate at the boundary between the stellar radiative and convective zones, it is speculated that magnetic braking is halted or at least much attenuated when the star becomes fully convective, and the boundary disappears.

Using the above equation to compute the orbital evolution, we find

$$\begin{aligned} \dot{\nu}_b &= +1.6\times10^{-14}\ \mathrm{Hz\ s^{-1}}\ m_1^{-1}(m_1+m_2)^{1/3} \\ &\times \left(\frac{\nu_b}{10^{-3}\ \mathrm{Hz}}\right)^{13/3}\left(\frac{R_2}{R_\odot}\right)^\gamma g(n,q). \end{aligned} \tag{6}$$

Thus, the evolution due to magnetic braking has nearly the same orbital frequency dependence as gravitational radiation. While the normalization is apparently much larger in this expression, one must realize that the companion stars in these systems are quite small. For typical accreting millisecond pulsar companion sizes of $R_2 \sim 0.05$–$0.1 M_\odot$ and $\gamma = 3$–4, the magnetic braking effect is reduced to be comparable with that of gravitational radiation.

Table 1 lists the five known accreting millisecond pulsars systems, including their orbital periods and estimated minimum companion masses. The primary masses were all assumed to be $1.4 M_\odot$ for simplicity. Also shown are the estimated orbital evolution rates due to GR and magnetic braking, according to the above equations. For the purposes of this evaluation, reasonable stellar radii were estimated based on the minimum companion masses. J1808 and J1814 were assumed to be fully non-degenerate, and the others degenerate (which leads to the sign difference in the orbital frequency derivatives between the two groups). If the true companions lie somewhere in between these two extremes, the effects on the magnitude of the orbital evolution rate will be somewhat moderated.

It is clear from the table that while in every case the magnetic braking torque is larger, in most cases it is only by a factor of a few. Given the potential uncertainties in the extrapolation of the magnetic braking effects from much higher mass stars to these low mass companions, it seems worthwhile to attempt to determine the actually orbital evolution rates. Whether or not it is possible to detect gravitational radiation as a separable effect, which it is likely not, I argue that determining the binary evolution rates provides a valuable reality check on evolutionary models.

5. MEASURING BINARY EVOLUTION

The binary parameters can be determined very precisely by pulsar pulse timing. It will likely not be possible to directly detect an orbital period change since, at the levels in Table 1, the period would only change by a few tens of microseconds, whereas typical measurement uncertainties are in the tens of milliseconds range. However, it is also possible to track the orbital *phase* evolution over time of a fiducial point, via pulse timing. Orbital phasing is in principle very sensitive since even a small frequency drift builds a cumulative phase error.

To be detectable, an orbital $\dot{\nu}_b$ term must be large enough to compensate for unknown orbital frequency errors and the uncertainty in determining the phase itself. We can estimate the total phase error, $\delta\phi_b$ as

$$\delta\phi_b = \delta\nu_b T + 1/2\dot{\nu}_b T^2 \tag{7}$$

where $\delta\nu_b$ is any frequency error and T is the time baseline over which the experiment is performed[2]. Clearly the advantage lies in long time baseline studies, so ultimately, the experiment may cross over between missions. Inter-mission time calibrations should not be an issue since, as already mentioned, the absolute phase need only be determined at the $\sim$ms level.

Under normal circumstances, the uncertainty in the orbital frequency will dominate over the $\dot{\nu}_b$ term. With two outbursts of the same source, spaced by several years, it will be possible to connect the orbital phase very precisely, and thus determine the orbital period precisely. With *three* outbursts of the same source it will then be possible to test for orbital evolution. J1808 has already had four outbursts in six years, and J1751 has had two outbursts in four years, so it is not unreasonable to have several recurrences of the same millisecond pulsar transient over the lifetime of a *RXTE* or future mission.

The statistical uncertainty in the orbital phase can be estimated as

$$\delta\phi_b = 0.018 \left(\frac{a \sin i}{10\ \mathrm{lt\ ms}}\right)^{-1} \left(\frac{\nu_s}{200\ \mathrm{Hz}}\right)^{-1} \sqrt{\frac{R_{\mathrm{tot}} + R_{\mathrm{bkg}}}{R_{\mathrm{psr}}^2 T}} \tag{8}$$

where i is the binary inclination to the observer's line of sight, ν_s is the pulse frequency, and $R_{\mathrm{psr,tot,bkg}}$ are the pulsed, total source, and background count rates in the detector, respectively. Rough estimates of this quantity are shown in Table 1. Where possible, these estimates have been compared to published or privately computed estimates of the orbital phase uncertainty from the actual pulse timing data, and the agreement is reasonably good. For example, while J1814 has a considerably longer orbital period than the other four systems, and was only active for a few weeks, the orbital phase uncertainty is smaller than for any of the other systems, because the pulsed fraction was much higher.

For an *RXTE*-like mission, the required time baseline to make a 3σ detection of the effects of gravitational radiation is about 8–17 years; and those of magnetic braking, about 3–9 years. Thus, it is only barely possible to be sensitive enough to detect the effects of GR within an *RXTE* lifetime, and then only for one of the five pulsar systems. On the other hand, with an enhanced timing mission, with (say) ten times the effective collecting area, it is possible to improve these numbers. Assuming the total pulsed fraction remains constant (including background), the estimated uncertainty in the orbital phase decreases by about a factor of three. The required time baseline for a 3σ detection of GR then falls below 9 years for all five millisecond systems, and for the ultra-

[2] Phase is expressed here in fractions of a cycle

TABLE 1. Orbital properties of the known millisecond accreting pulsars, including primary and companion masses (m_1 and m_2); orbital period (P_b); estimated uncertainty in the orbital phase ($\delta\phi_b$); and estimated frequency evolution by gravitational radiation and magnetic braking, $\dot{\nu}_{b,\mathrm{GR/MB}}$. J1751, J0929 and J1807 are assumed to be degenerate and have radii of $0.05 R_\odot$; J1808 and J1814 are assumed to be non-degenerate and have radii of 0.12 and 0.35 $R_\odot$, respectively.

Name	m_1	m_2	P_b	$\delta\phi_b$	$\dot{\nu}_{b,\mathrm{GR}}$ **[s^{-2}]**	$\dot{\nu}_{b,\mathrm{MB}}$ **[s^{-2}]**
XTE J1751–305	~ 1.4	> 0.013	2.5 ks	8×10^{-5}	-1×10^{-20}	-4×10^{-20}
XTE J1807–294	~ 1.4	> 0.007	2.4 ks	1×10^{-4}	-6×10^{-21}	-5×10^{-20}
XTE J0929–314	~ 1.4	> 0.01	2.6 ks	3×10^{-4}	-7×10^{-21}	-4×10^{-20}
SAX J1808.4–3658	~ 1.4	> 0.05	7.2 ks	8×10^{-5}	$+4\times10^{-22}$	$+3\times10^{-21}$
XTE J1814–338	~ 1.4	> 0.16	15.0 ks	4×10^{-6}	$+9\times10^{-23}$	$+4\times10^{-21}$

compact systems like J1751 or J1807, drops to within 4–5 years. Of course, magnetic braking is likely to be stronger than GR, so its effects may swamp any GR signal, but that is important to know as well! The GR effect *must* be there, so an enhanced timing mission should be designed to detect the effects of GR if possible.

One caveat is hidden in the phrase, "the total pulsed fraction remains constant," which assumes that the total particle background rate in an enhanced timing mission does not increase by more than the increase in collecting area. If a change in detector technologies causes an appreciable increase in the particle background (by a factor of $\sim$2 more than any area increase), then the gains due to collecting area increases will be largely negated. Thus, the background should be kept as low or lower than *RXTE* per unit area.

It should also be pointed out that binary orbit evolution can be detected from eclipsing systems. In the case of EXO 0748$-$676, the best studied eclipsing low mass X-ray binary with a 7.1 hr orbital period, the eclipse times of arrival have been tracked for more than 20 years (Wolff et al. [31]; see also Wolff, this volume). Orbital period change is clearly detected, but oddly, the period is *increasing* at a rate of $\dot{P}_b/P_b \sim 5\times10^{-8}$ yr^{-1}, whereas normal accretion theory would predict orbital period decrease as angular momentum is removed. One lesson that we should take from this fact is that the orbital behavior of the millisecond systems may not behave as expected (for example, the evolutions predicted by GR and MB from the above equations is a factor of $\sim$100 smaller than that observed). The orbital phase advances detected by Wolff et al. [31] from EXO 0748$-$676 are of order $\sim$100 s, or $\Delta\phi_b \sim 4\times10^{-3}$; clearly for the millisecond pulsar systems we can do much better than this, and are thus more sensitive to equivalent scale period change.

6. SPIN TORQUES

Another topic for future studies of millisecond pulsars regards their spin evolution. It is well understood that the accretion disk in low mass X-ray binaries should apply a torque to the neutron star (Ghosh & Lamb [10]), although in principle the sign of the torque depends on the configurations of the neutron star magnetic field and boundary layer within the disk. If the so-called Alfvén radius lies within the co-rotation radius, then the pulsar is expected spin up according to the relation

$$\dot{\nu}_s \propto \dot{M}^{6/7}, \qquad (9)$$

where $\dot{M}$ is the mass accretion rate onto the neutron star. This formalism is known to work quite well for AO535+262 and GRO J1744$-$28 (Bildsten et al. [2]), and SAX J2103.5+4545 (Baykal, Stark & Swank [1]).

Does the same formalism apply to the millisecond pulsars? Published results for J0929 suggests that the neutron star was actually spinning *down* at a rate of $\dot{f} \sim -10^{-13}$ Hz s^{-1}. Recent work by Rappaport et al. [22] suggests that a Ghosh- & Lamb-type of mechanism may be applicable, and may produce both positive and negative torques, with a crossover point which depends on the neutron star surface magnetic field. According to those models, the rate of spin change should be a smooth function of the mass accretion rate.

In the case of J1807, however, we find that the apparent pulsar spin evolution most definitely is *not* a smooth function of the mass accretion rate. We performed a pulse timing analysis for the complete outburst of Spring 2003, until pulsations were no longer detectable. Spin frequencies and derivatives were estimated by fitting a piecewise polynomial to the residual phases, after apply a simple constant-frequency model. Figure 2 shows the apparent spin change rate as a function of estimated mass accretion rate. There are wild swings in the apparent spin frequency, of both signs, at the *same* value of the mass accretion rate. Similar phenomena have been seen in other of the five systems, where long enough baselines exist (J1751 & J1808, Markwardt [15]; J1808, Morgan et al. [16]).

Thus, one of two things is true: either the spin evolution is not a direct function of the mass accretion rate, or the apparent spin frequency is not the *true* spin fre-

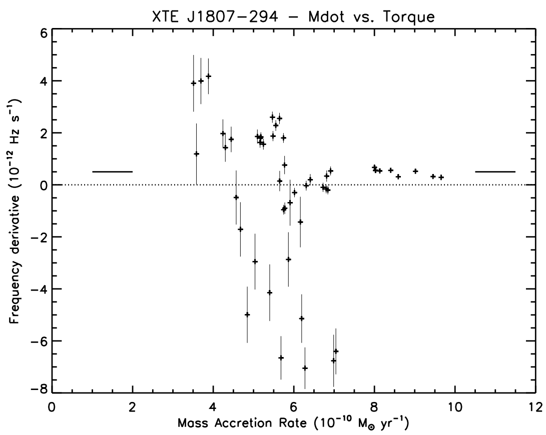

FIGURE 2. The apparent spin frequency derivative as a function of mass accretion rate for XTE J1807−294. A nominal Ghosh & Lamb [10]-type spindown rate is indicated by the horizontal bars.

quency. The latter could be true if the emission region (the "hot spot") is not fixed on the surface of the neutron star. The apparent frequency changes in J1807 (Figure 2) are based on fractional phase changes of ± 0.15, but never more than one full cycle. It seems possible that the position of the hot spot may move in response to reconfigurations of the outer accretion disk and the magnetosphere of the neutron star. An example of this closer to home can be seen at Jupiter. The Jovian aurora is formed where charged particles are channeled to the polar regions. The Jovian moons, sources of charged particles, map to specific and identifiable footpoints in the auroral ring (Clarke et al. [6]). As the Jovian magnetosphere adjusts to ionic storms, and as the Jovian moons orbit the planet, the shape and position of the auroral ring changes with time. In a similar manner, it is possible that the position of the pulsar hot spot changes with time in response to variations in the structure of the inner accretion disk.

7. PULSE PHASED SPECTROSCOPY

One exciting new area of research appears to be pulse phased spectroscopy. Several new papers have appeared in the past 1–2 years which attempt to simultaneously fit the spectrum as a function of spin phase (Poutanen & Gierliński [20]; Bhattacharyya et al. [Bhattacharyya et al. 2004]; also see Poutanen, this volume). These models assume some form of initial emission pattern at the neutron star surface, and then propagate the signal, including Doppler and relativistic effects. Because the fit is highly constrained by the fundamental and its harmonics, the stellar compactness ($= M_1/R_1$) can be quite narrowly constrained as well. Using different emission models, both Poutanen & Gierliński (for J1808) and Bhattacharyya (for J1814) find a narrow region of phase space which is allowed. Presumably a similar kind of analysis can be done for the other pulsars.

The question is whether the constraints from this kind of analysis could be improved with an enhanced timing mission. While increased effective area will reduce the statistical errors, in most cases *RXTE* spectral data is limitd by systematic rather than statistical errors. Indeed, Poutanen & Gierliński [20] comment that they are probably close to the systematics limit for their analysis of J1808. Also, the modeling itself may introduce systematic uncertainties (i.e. uniqueness questions). Thus, to make further improvements in this effort, a corresponding reduction in the systematic errors will be required, which may be difficult to achieve, but worth pursuing.

8. OTHER INVESTIGATIONS

Several other issues come to mind, which I will mention briefly in the form of questions:

- Why are pulsations not seen in most LMXBs? Is the magnetic field too low? Or screened? (Cumming et al. [7]). Titarchuk et al. [26] argue that coronal optical depths are higher in LMXBs, leading to smeared pulsations.
- Can the mean mass transfer rates be measured? This would involve measuring the mean X-ray flux, integrated over multiple recurrences. This in turn could be compared to the mass transfer rates predicted by the above binary evolution formulae.
- Does the "propeller" regime ever occur? Current observations are consistent with pulsations always being present at some fraction of the persistent emission, over a factor of $\sim$100 in luminosity variation. A factor of $\sim$ 10 in collecting area would extend the luminosity range of detectable pulsations to a factor of $\sim$ 1000. If pulsations were detectable over such a wide range of luminosities (and hence mass accretion rates), how can the original Ghosh & Lamb [10] model still hold?

9. CONCLUSIONS

Finally, I conclude with some remarks regarding the optimal mission for detecting and studying accreting millisecond pulsars.

- **Monitoring.** All five of the known sources are transients, with peak fluxes in the range 25–60 mCrab. Thus, a monitoring program will be required to detect new and recurring ones, either as a part of an all-sky monitor (which can reach sensitivies of a few mCrab per day); or as part of a dedicated scanning/rastering program to monitor a large region in a short amount of time.

- **Follow-up.** The known outbursts last for a variable amount of time. In some cases the outbursts were complete within 1–2 weeks (J1808, J1751) and in others the activity persisted for months (J1807). For the short transients it is crucial to follow-up quickly, within a few days, but it is impossible to know ahead of time which will be long and which short duration.
- **Background.** The particle background count rate per collecting area should not increase beyond the PCA, or else the gains due to increased collecting area may be partially or fully negated.

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